Winter Wheat Vegetation Indices
Calculated from Combinations of Seven Spectral Bands

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Spectral reflectance data were obtained for winter wheat over a full growing season. Four irrigation treatments, applied to six genotypes, provided a variety of crop growth conditions. Leaf area index, green ground cover, total wet and total dry phytomass, and leaf phytomass measurements were taken monthly during the winter and biweekly during the spring. Reflectance measurements were made with a radiometer having three visible, two near-IR and two mid-IR bands. Vegetation indices, calculated from various band combinations, were linearly related to the five plant parameters. Of the 1240 vegetation indices formed, ratio indices had the higher (0.79–0.86) coefficients of determination (r^2) than N-space greenness (0.61–0.81) when related to the plant parameters. The commonly used IR/red ratio produced considerably lower r^2 values than many of the other ratio indices. The mid-IR bands appeared more frequently in the ratio indices than in the greenness indices. The results show the relative merits of the seven bands, when combined into vegetation indices, to estimate various plant parameters.

Introduction

The estimation of crop growth parameters such as leaf area index (LAI) and phytomass from spectral measurements could provide valuable inputs to crop growth and yield models. A number of spectral indicators have been proposed for this purpose. They include individual band reflectance factors, linear combinations of bands by multiple regression, orthogonal "greenness," and ratios of infrared and red bands (Ahlrichs and Bauer, 1983; Best and Harlan, 1985; Hatfield

et al., 1985; Tucker, 1978; Aase and Siddoway, 1980; 1981).

Ahlrichs and Bauer (1983) found good correlations between individual band reflectances and five plant parameters for spring wheat canopies. Correlations between the plant parameters and several ratio indices and with the orthogonal greenness index were slightly higher than for the individual band reflectance factors. They found the highest correlations of spectral data and their plant parameters to occur between tillering and anthesis.

Best and Harlan (1985) also found that spectral transformations were better correlated with LAI than were individual band reflectance factors. They measured spectral reflectance factors for oats with a boom-mounted radiometer with bands that simulate those of the thematic mapper (TM) on Landsat-5. Multiple regression analysis was used to select the bands that, in linear combinations, provided the highest correlations with LAI. Their highest r^2 (using TM bands 3, 4, and 5) was 0.708, which was less than the r^2 values reported by Ahlrichs and Bauer for a number of band combinations. This difference may be due to the fact that Best and Harlan used full season data, whereas Ahlrichs and Bauer used data only from seedling to anthesis.

In relating greenness to LAI, Best and Harlan (1985) found that an exponential model fit their data very well if a separate set of coefficients were determined for periods before and after maximum LAI. This result is in agreement with those of Kollenkark et al. (1982) where exponential equations of spectral data were found to produce high correlations when estimating soybean parameters.

Hatfield et al. (1985) examined the relationship between LAI and several spectral transformations for wheat with different seeding dates. They showed that greenness was not unique for all planting dates but that the IR/red ratio reasonably independent of seeding date.

The IR/red ratio and the functionally equivalent normalized difference (ND) (Perry and Lautenslager, 1984) have been widely used as vegetation indices (Rouse et al., 1973; Richardson and Wiegand, 1977; Wiegand et al., 1979; Richardson et al., 1982). These indices have physical significance in that the IR reflectance increases and the red reflectance decreases with increasing vegetation. The mid-IR bands of the TM are purported to be sensitive to water in plants (Tucker, 1980). The multiple regression results of Ahlrichs and Bauer (1983) and of Best and Harlan (1985) indicate that the inclusion of mid-IR bands improve the correlations between spectral data and plant properties. However, the use of the mid-IR bands in ratio-type indices has received little attention.

Our objectives were to calculate ratio and N-space greenness indices for all combinations of seven spectral bands and to relate the indices derived to five winter wheat growth parameters for the purpose of identifying the indices and predominant bands that are the most highly correlated with the several plant parameters.

Procedure

A field study was conducted at the USDA Conservation and Production Research Laboratory at Bushland, TX. (Southern High Plains) during the 1981–1982 cropping season. Six different winter wheat (*Triticum aestivum* L.) genotypes; (TAM 101, TAM 105, Vona, Scout 66, Sturdy, and TAM 108) were selected to represent differences in height, phytomass, harvest index, and drought tolerance. The six genotypes were subjected to a wide range of water deficits established by the following four irrigation treatments: (I-1) two 100 mm irrigations during vegetative development; (I-2) two 100 mm irrigations during the reproductive stages of development; (I-3) no irrigations; and (I-4) four seasonal irrigations two during vegetative development and two during the reproductive stages, each irrigation being 100 mm. The four

irrigation treatments and six genotypes provided a wide range of vegetative conditions for relating spectral data and canopy vegetative values that are useful in crop condition assessment and modeling. The experimental plots consisted of 36 30×10 m leveled and flood irrigated basins seeded to winter wheat. Each irrigation treatment consisted of three adjacent basins in which one-half of each was seeded to one of the six genotypes. Treatments were replicated three times. Each replication also included a wet (maintained by irrigation) and dry plot of bare soil for use in calculating N-space indices. The soil was Pullman clay loam, the predominant soil of the Southern High Plains and a member of the fine, mixed, thermic family of Torrertic Paleustolls.

Plant measurements

Plants were sampled at approximately monthly intervals until spring regrowth began. At that time a biweekly sampling schedule was initiated. Plant data were obtained by sampling two 1-m length rows (0.5 m²) of each plot. Plant counts of the total sample were obtained during the early part of the season until plants became so entangled they could not be separated, at which time the average plant density as determined from all previous dates, was used for calculating plant parameters to an area basis. Within the sampled area, 10 plants from each sampled row, or later in the growing season, 20 tillers were selected at random as a subsample. Tiller counts, leaf area index (LAI), and green leaf phytomass measurements were determined from these subsamples. Subsequently, wet phytomass and dry phytomass were determined from the main sample plus the subsample.

The fraction of ground covered by photosynthetically active vegetation was determined using a dot-grid method. Color slides taken by a vertically mounted camera were projected on a screen on which 50 dots were superimposed at random. Dots touching green vegetation were counted and divided by the total to obtain the fraction of green ground cover. A value of zero green ground cover was determined on several occasions when data were taken over mostly senesced vegetation.

Spectral measurements

Spectral data were obtained with a Barnes MMR 12-1000 radiometer (MMR)[1] (Table 1) (Robinson et al., 1979). The radiometer and the remotely operated camera were mounted on the boom of a "high-boy" tractor in a nadir position 5 m above ground level. With a 15° field of view, the radiometer scanned a circle of approximately 1.3 m diameter at ground level. Measurements were made as the tractor was moving at about 0.5 m/s in a north–south direction. Data were recorded by an Omnidata Polycorder[1] programmed to record 20 ms averages of voltages from each of the eight channels, and to repeat the sequence five times per plot. This sequence allowed a real averaging of the plot (1/2 of each leveled basin). The five readings per plot were then averaged by the Polycorder for downloading to a computer.

A measurement sequence over a replication of all treatments required about 20 min. Readings were taken over a

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[1]Mention of a trade name or product does not constitute a recommendation or endorsement for use by the U.S. Department of Agriculture.

calibrated 1.2 m^2 painted BaSO$_4$ reference panel, followed by a dark reference (no light). Then a set of readings from each plot of the replication, followed by a second measurement of the reference panel and dark background. The reference data were then averaged and corrected for total irradiance and divided into the target voltages to obtain reflectances. Measurements of the three replications were made between the hours of 1030 and 1200 (Central Standard Time) on days with full sun. Spectral measurements were obtained for five dates during the winter growth period prior to spring tillering, ten dates from tiller elongation to heading, eight dates after heading, and one date at maturity.

Data analysis

Vegetation indices were developed from the seven reflectance bands of the Barnes MMR. The indices consisted of individual bands, various band ratios, ratios of differences divided by sums (normalized difference), and linear combinations (N-space). In total, 1340 vegetation indices were calculated. Each index was linearly related to each of five plant parameters: leaf area index, fraction of ground covered by green vegetation, total wet phytomass, total dry phytomass, and dry green leaf phytomass.

Band ratios (1120) were calculated as the seven individual bands, 42 two-band combinations, 210 combinations of three bands as either $a/(b*c)$ and $(a*b)/c$, 210 four-band combinations as $(a*b)/(c*d)$, 420 five-band combinations as $(a*b)/(c*d*e)$ and $(a*b*c)/(d*e)$, 140 six-band combinations as $(a*b*c)/(d*e*f)$, and 70 seven-band combinations as $(a*b*c)/(d*e*f*g)$ and $(a*b*c*d)$ $/(e*f*g)$. Normalized differences (ND) were calculated for the 21 possible two-band combinations.

Greenness values were calculated for all band combinations (120 possible) from 2-space to 7-space (Jackson, 1983). Our greenness values differ slightly from those calculated using the technique of Kauth and Thomas (1976) in that a greenness value for bare soil was calculated and subtracted from all greenness values.

Results and Discussion

The indices used as the independent variables in linear regressing with the plant growth parameters were ranked according to the r^2 values and presented in two part tables when applicable. The first part presents the ratio indices with the corresponding slope, intercept, standard error of the slope (S_b) and r^2 values along with the values obtained for the ND, the IR/red ratio and N-space 3,4 (PVI)—three commonly used red–IR vegetation indices. The second part contains the bands used to calculate greenness and the slope, intercept, S_b and r^2 from regression with the plant parameters. Also given are the band coefficients for calculating the greenness index, including the soil constant needed to make all greenness values zero for bare soil.

Leaf area index

The seasonal course of winter wheat LAI for the dryland and fully irrigated treatments of one genotype (TAM 105) is shown in Fig. 1. The LAI is the same for the two treatments until about 180 days after seeding, when water deficits inhibited leaf area expansion of the dryland treatment. The highest LAI in Fig. 1
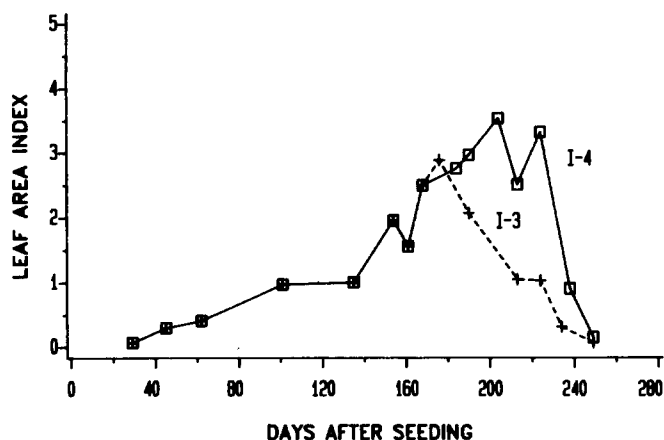
FIGURE 1. Seasonal development of leaf area index for two irrigation treatments (I − 3 and I − 4 of the variety TAM 105).

was about 3.5 but reached as high as 4.5 for other genotypes and irrigation treatments.

The five ratio indices that produced the highest r^2 when regressed with LAI are shown in Table 2. The ratio $(4*6)/3$ had the highest r^2 value. The data for this relation are plotted in Fig. 2. Of the top five indices, MMR band 3 (visible red) appeared in the denominator of four, and MMR band 4 (near-IR) was in the numerator of all the equations. This lends support to the long-held concept that the ratio of near-IR to visible red bands is well related to leaf area index. However, the two band ratio MMR4/MMR3 did not appear in the top equations as ranked by r^2 values but ranked 131 with an r^2 value of 0.679. The ND of MMR3 and 4 was ranked 167 with an r^2 value of 0.642.

The use of N-space 3,4 with an r^2 value of 0.808 would have ranked 23 if it were compared with the ratio indices.

The second part of Table 2 shows results of regressing LAI versus N-space greenness. The r^2 values are slightly less than for the ratio indices. MMR4 appears in the top five, and MMR1 and MMR2 appear in four of the top five. The first appearance of MMR3 was in the fifth index. The mid-IR bands MMR6 and MMR7 were not used in any of the ranked N-space indices. The data for the relation between LAI and the best greenness index according to r^2 are plotted in Fig. 3.

Green ground cover

The five ratio indices that produced the highest r^2 when regressed with per-

TABLE 1 Wavelength Intervals for the Eight-Band Barnes 12-1000 MMR and the Corresponding Thematic Mapper Bands

MMR Band	Wavelength Interval (μm)	TM Band
1	0.45–0.52	1
2	0.52–0.60	2
3	0.63–0.69	3
4	0.76–0.90	4
5	1.15–1.30	—
6	1.55–1.75	5
7	2.08–2.35	7
8	10.40–2.50	6

TABLE 2   Slopes, Intercepts, r^2 and S_b Values from Linear Regression of Five Ratio and Five
N-Space Greenness Indices and Leaf Area Index[a]

RATIO INDICES

RANK	RATIO	SLOPE	INTERCEPT	S_b	r^2
1	$(4*6)/3$	0.0144	− 0.194	0.0004	0.85
2	$(4*6)/1$	0.0162	− 1.144	0.0004	0.85
3	$(2*4*5*7)/(1*3*6)$	0.0127	− 0.301	0.0003	0.85
4	$(1*4*6)/(2*3)$	0.0237	− 0.282	0.0006	0.85
5	$(2*4*6)/(1*3)$	0.0087	− 0.094	0.0002	0.85
131	$4/3$	0.1385	0.440	0.0058	0.68
167	$(4-3)/(4+3)$	5.1473	1.913	0.2330	0.64
21	N-space 3, 4	0.1731	− 0.640	0.0051	0.81

N-SPACE GREENNESS INDICES

RANK	BANDS	SLOPE	INTERCEPT	S_b	r^2
1	2, 4	0.239	− 0.609	0.0068	0.82
2	1, 2, 4	0.206	− 0.631	0.0059	0.82
3	1, 4	0.306	− 0.669	0.0087	0.82
4	1, 2, 4, 5	0.189	0.251	0.0055	0.81
5	1, 2, 3, 4	0.155	− 0.639	0.0045	0.81

GREENNESS COEFFICIENTS

RANK	SOIL CONSTANT	BAND 1	2	3	4	5	6	7
1	0.98		− 0.864		0.503			
2	1.22	− 0.479	− 0.653		0.586			
3	0.92	− 0.919			0.393			
4	4.30	− 0.379	− 0.516		0.737	− 0.212		
5	1.47	− 0.232	− 0.316	− 0.549	0.737			

[a]Also shown are the rank and other values derived for the three most commonly used red–IR VIs.
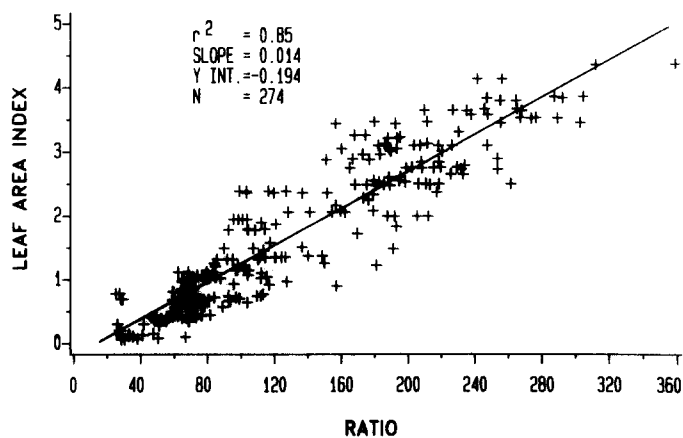

FIGURE 2.   The relation between the ratio index $[(4*6)/3]$ and leaf area
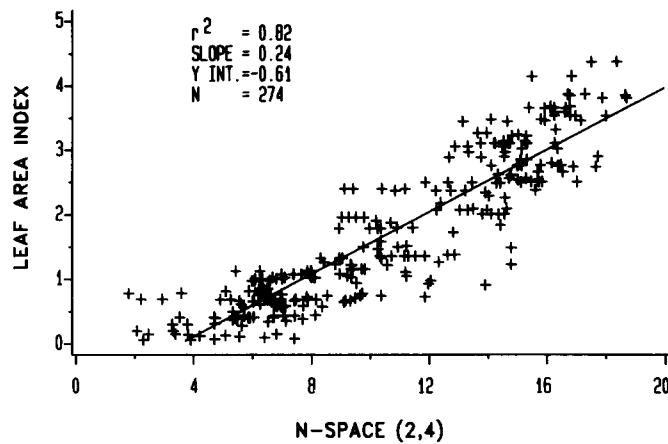index that produced the highest r^2 value.

FIGURE 3. Relation of the N-space greenness index and leaf area index that produced the highest r^2 value.

TABLE 3 Slopes, Intercepts, r^2 and S_b Values from Linear Regression of Five Ratio and Five N-Space Greenness Indices and Green Ground Cover[a]

RANK	RATIO	SLOPE	INTERCEPT	S_b	R^2
		RATIO INDICES			
1	$(2*3*5)/(1*4*6)$	− 104.3	113.9	2.49	0.86
2	$(2*3)/(4*7)$	− 366.5	105.1	8.79	0.86
3	$(2*3)/(1*6)$	− 159.5	134.5	3.90	0.86
4	$(3*6)/(5*7)$	− 199.1	135.9	4.87	0.86
5	$(2*3*6)/(1*4*7)$	− 80.5	112.6	2.03	0.85
312	$4/3$	2.5	45.6	0.15	0.48
63	$(4 − 3)/(4 + 3)$	122.9	17.5	4.36	0.74
115	N-space 3,4	3.5	21.2	0.15	0.67

RANK	BANDS	SLOPE	INTERCEPT	S_b	R^2
		N-SPACE GREENNESS INDICES			
1	3,7	26.64	195.22	1.10	0.69
2	1,3,7	26.52	22.14	1.19	0.67
3	3,4	3.51	21.15	0.15	0.67
4	3,4,5	3.04	22.83	0.14	0.67
5	2,3,4	3.22	21.55	0.13	0.66

RANK	SOIL CONSTANT	1	2	3	4	5	6	7
				GREENNESS COEFFICIENTS — BAND				
1	4.02			− 0.911				0.410
2	− 4.27	− 0.195		− 0.876				0.440
3	1.24			− 0.771	0.636			
4	0.86			− 0.698	− 0.708	− 0.102		
5	1.38		− 0.355	− 0.608	− 0.709			

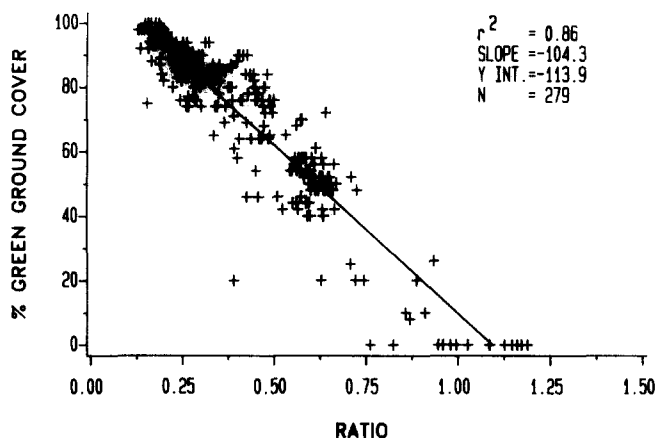[a]Also shown are the rank and other values derived for the three most commonly used red–IR VIs.

FIGURE 4. Relation between the ratio index $[(2*3*5)/(1*4*6)]$ and percent green ground cover that had the highest r^2 value.

cent green ground cover are listed in Table 3. The ratio $(2*3*5)/(1*4*6)$ proved the best estimator of green ground cover. The data for this relation and the best fit regression are shown in Fig. 4. The zero green ground cover data in Fig. 4 are mostly senesced vegetation. Of the five indices shown in Table 3, band 3 (visible red) appears in the numerator of all five and band 4 (near-IR) appeared in the denominator of all five. This is in contrast to the LAI relations, where band 3 is always located in the denominator and band 4 in the numerator. The use of the IR/red ratio was ranked 312 in the ratios with an r^2 value of 0.481 whereas the ND with an r^2 value of 0.741 was ranked 63. The use of bands 3 and 4 as an N-space index was ranked 112 for the overall set of data.

The N-space greenness indices (shown in part two of Table 3) had considerably lower r^2 values when regressed to green ground cover than the ratio indices. The top r^2 values for greenness ranged from 0.69 to 0.66, with bands 3 and 7 providing the highest r^2 value. Band 3 appeared in all of the greenness indices as with the ratio indices, and band 4 was in three, indicating the predominant value

of these bands in estimating green ground cover. With the exception of the two top-ranked indices shown, the mid-IR bands were not used in the top 10% of the N-space indices.

Phytomass

The ratio indices that yielded the highest r^2 when regressed against total wet and dry phytomass are presented in Table 4. Linear regression relationship of N-space greenness indices and phytomass are not given since the r^2 values obtained (> 0.5) were much lower than for the ratio indices. For both wet and dry phytomass, the ratios contained MMR bands 6 and 7, singularly or in combination of all the indices presented. MMR7 was the dominant occurring band, appearing in eight of the 10 indices for estimation of wet and dry phytomass and as the denominator of all the indices. This indicates the benefits of the water absorption bands in estimating total phytomass of wheat. MMR band 3 appeared frequently in the numerator (six indices), often in combination with MMR4 or MMR5. Figures 5 and 6 show the phytomass data versus the ratio index that produced the

TABLE 4 Slopes, Intercepts, r^2 and S_b Values from Linear Regression of Five Ratio Indices and the Wet and Dry Phytomass of Winter Wheat[a]

		WET PHYTOMASS			
RANK	RATIO	SLOPE	INTERCEPT	S_b	r^2
1	2/(6*7)	44578.8	− 290.1	1223.3	0.83
2	(3*4)/(1*6)	1441.1	− 2277.8	39.8	0.83
3	(3*5)/(2*6*7)	6549.3	− 166.8	178.5	0.83
4	(3*5)/(1*6*7)	3895.2	− 72.0	106.6	0.83
5	1/(6*7)	75445.1	− 418.1	2104.5	0.83
372	4/3	108.0	541.1	7.0	0.46
385	(4 − 3)/(4 + 3)	3781.2	1134.3	285.1	0.39
407	N-space 3,4	85.3	361.9	9.6	0.22

		DRY PHYTOMASS			
RANK	RATIO	SLOPE	INTERCEPT	S_b	r^2
1	(2*5)/(4*6*7)	25868.9	− 433.7	666.3	0.83
2	(3*4)/(1*5*6)	10790.0	− 543.6	272.4	0.82
3	3/(1*7)	4050.2	− 353.3	101.1	0.81
4	2/(5*7)	48373.5	− 539.4	1277.1	0.81
5	3/(2*7)	6932.2	− 429.3	179.8	0.81
389	4/3	27.6	286.1	3.6	0.18
405	(4 − 3)/(4 + 3)	832.0	48.0	141.7	0.12
441	N-space 3,4	10.5	393.5	4.4	0.02

[a]Also shown are the rank and other values derived for the three most commonly used red–IR VIs.

highest r^2 values. In both figures the linear equations adequately describe the relationships with phytomass. The use of MMR3 and 4 in a ratio or linear combination produced very low r^2 values.

The data represent a wide range of plant water stress conditions. Under some conditions the total water content of the plant canopy may be of interest. This factor, the difference between wet and dry phytomass, was calculated and regressed versus the various ratio indices. The highest r^2 values (0.82) resulted from using the ratio (3*4)/(1*6), which is
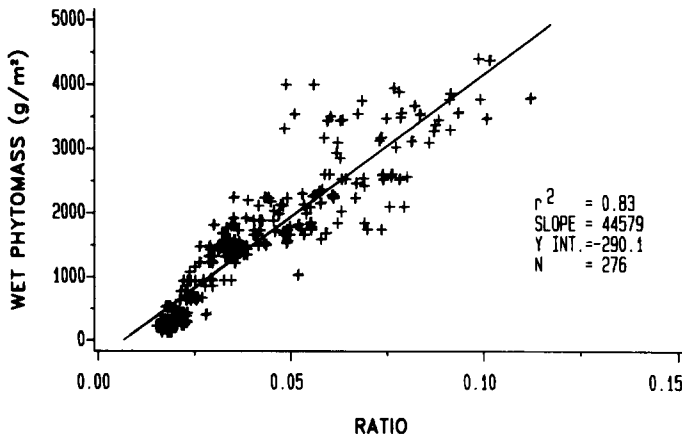

FIGURE 5. Relation between the ratio index [2/(6*7)] and total wet phytomass that produced the highest r^2 value.
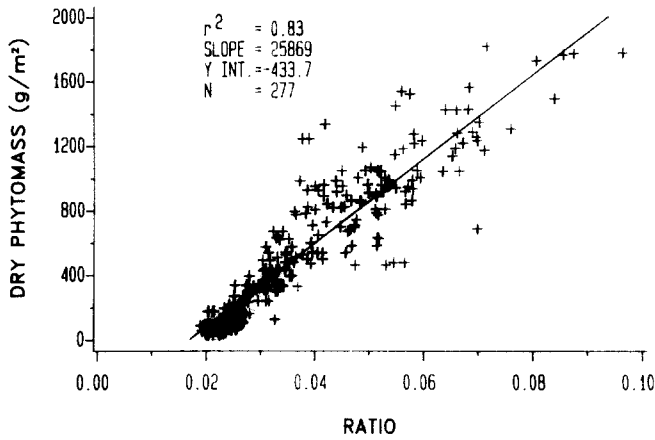
FIGURE 6.   Relation between ratio index $[(2*5)/(4*6*7)]$ and total dry
phytomass that produced the highest r^2 value.

TABLE 5   Slopes, Intercepts, r^2 and S_b Values from Linear Regression of Five and Five
N-Space Indices and Dry Green Leaf Phytomass[a]

		RATIO INDICES			
RANK	RATIO	SLOPE	INTERCEPT	S_b	r^2
1	$(1*5*6)/(2*3)$	2.873	-67.31	0.093	0.79
2	$(5*6)/3$	1.740	-55.27	0.059	0.78
3	$(2*5)/3$	8.959	-118.76	0.301	0.78
4	$(1*5)/3$	14.523	-130.38	0.499	0.77
5	$(4*5*7)/(2*6)$	3.100	-120.68	0.109	0.76
300	$4/3$	8.312	68.34	0.640	0.40
175	$(4-3)/(4+3)$	364.438	109.90	22.412	0.51
20	N-space 3, 4	13.228	-29.63	0.552	0.69

		N-SPACE GREENNESS INDICES			
RANK	BANDS	SLOPE	INTERCEPT	S_b	r^2
1	2, 5	43.32	-72.59	1.582	0.75
2	1, 2, 5	36.46	-76.57	1.348	0.74
3	2, 3, 5	24.78	-69.61	0.923	0.74
4	1, 2, 3, 5	24.05	-71.20	0.896	0.74
5	1, 2, 3, 5, 6	22.14	-60.44	0.828	0.74

		GREENNESS COEFFICIENTS						
	SOIL	BAND						
RANK	CONSTANT	1	2	3	4	5	6	7
1	2.08		-0.911			0.411		
2	2.55	-0.515	-0.704			0.488		
3	3.09		-0.360	-0.703		0.612		
4	3.23	-0.238	-0.327	-0.650		0.642		
5	4.06	-0.173	-0.238	-0.515		0.773	-0.223	

[a]Also shown are the rank and other values derived for the three most commonly used red–IR VIs.
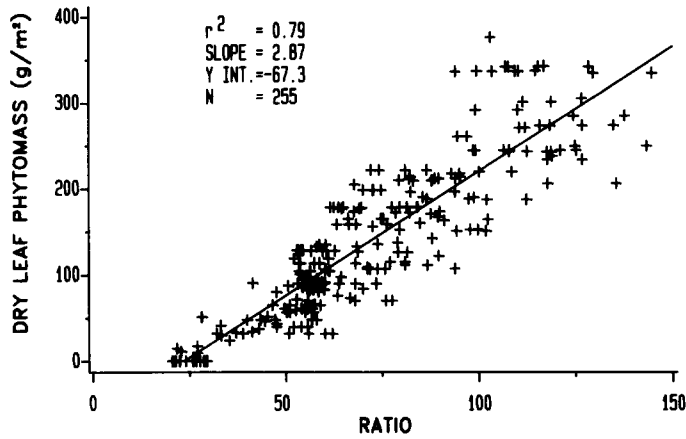
FIGURE 7.   Relation between the ratio index $[(1*5*6)/(2*3)]$ and dry green leaf phytomass that produced the highest r^2 value.

also a ranked ratio for the estimation of wet phytomass.

Dry green leaf phytomass

The dry green leaf phytomass has been related to LAI by Aase (1978) and LeMaster et al. (1980) as a possible and less tedious method for field LAI determinations. Thus, we related the indices to leaf phytomass as a possible estimator of LAI. The highest ranked indices for estimating leaf phytomass as opposed to LAI estimations were dominated by MMR5 in the numerator and MMR3 in the denominator (Table 5). MMR band 4 did not appear until the fifth rank and that was in combination with MMR5.

MMR bands 2 and 5 were dominant in the N-space greenness indices for leaf phytomass and had slightly lower regression values. MMR4 did not appear in the top five ranked indices and was totally replaced by MMR5. The relationship for the highest ranked ratio versus dry green leaf phytomass is shown in Fig. 7.

Concluding Remarks

The trends of the MMR bands used in the highest ranked indices for each plant parameter are summarized in Table 6. Bands appearing as trends of the ratio indices are indicated by a D (denominator) or N (numerator). Band 3 appears in all of the indices occurring three of five

TABLE 6   MMR Band Trends of the Ratio Indices That Produced the Highest r^2 Values When Regressed with the Indicated Plant Parameter

| | MMR BAND[a] | | | | | | |
PLANT PARAMETER	1	2	3	4	5	6	7
Leaf area index	D		D	N		N	
Green ground cover	D	N	N	D			D
Wet phytomass			N			D	D
Dry phytomass			N				D
Dry green leaf phytomass			D		N		

[a] The letters D and N indicate the band appeared in the denominator or numerator of the ratio, respectively.

times in the numerator and band 4 in only two indices (LAI and ground cover), once as a numerator and once as a denominator. This is a somewhat surprising result when one considers that the near-IR/red ratio is perhaps the most frequently used vegetation discriminator. Also to be noted, is that either MMR band 6 or 7 was combined into the ratios for estimating four of the parameters (excluding leaf phytomass) and are somewhat dominant in estimating wet and dry phytomass. Of the five plant parameters reported here, ratio indices produced higher r^2 values than N-space greenness indices for all of the five parameters tested. Qualitative comparison of the figures indicate that the indices are linearly related to the plant parameter and can be used as a simple method for estimating the parameter desired. The estimation relationships apply to a wide range of winter wheat vegetative development, representing genotypes commonly grown in the Southern High Plains with major water stress during various developmental stages.

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